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04/30/99

April 30, 1999

Box Patent Applications
Assistant Commissioner for Patents
Washington, DC 20231

SUBJECT: A FILTER SYSTEM WITH REDUCED SWITCH THERMAL NOISE AND A ΣΔ MODULATOR USING SUCH A FILTER
AD-200J

Dear Sir:

Enclosed is a patent application including formal papers as follows:

Applicant: Adams et al..

Title: A FILTER SYSTEM WITH REDUCED SWITCH THERMAL NOISE AND A ΣΔ MODULATOR USING SUCH A FILTER

No. Pages Specification: 8; Claims: 5; Abstract of Disclosure: 1; Drawings: 2

Filing Fee Calculation

Basic Fee:	$ 760.00
Additional Fees:	
Total number of claims in excess of 20: 0 x $18.00	$ 0.00
Number of independent claims in excess of 3: 1 x $78.00	$ 78.00
TOTAL FILING FEE:	$ 838.00

EXPRESS MAIL CERTIFICATE NO. EM589304477US

A check in the amount of $838.00 for the filing fee is enclosed. If any payment during prosecution is found to be incorrect, please charge any deficiency or credit any overpayment to my Deposit Account 09-0002. A copy of this letter is enclosed for use by the Finance Branch in the event that it is necessary to make any charge or credit to my deposit account.

If for any reason this APPLICATION is found to be incomplete, or if at any time it appears that a telephone conference with counsel would help advance prosecution, please telephone the undersigned collect in Waltham, Massachusetts, (781) 890-5678.

In addition, pursuant to rule 1.136(a)(3), the office is hereby authorized to treat any future reply requiring an extension of time as incorporating a request therefore. Also, any request or Petition for an Extension of time notwithstanding an inadvertent reference in the Petition to a shorter period of time is to be treated as requesting the appropriate length of time.

Kindly acknowledge receipt of the foregoing by returning the enclosed self-addressed postcard.

Very truly yours,

Joseph S. Iandiorio
Reg. No. 23,095

JSI:abh
Enclosures

APPLICATION

FOR

UNITED STATES LETTERS PATENT

Be it known that we, Robert Adams, residing at 19 Overlook Drive, Acton, Massachusetts 01720, and being a citizen of the United States; and Gangadhar Burra residing at 1 Kingman Road, Acton, Massachusetts 01720, and being a citizen of India, have invented a certain new and useful

A FILTER SYSTEM WITH REDUCED SWITCH THERMAL NOISE AND A ΣΔ MODULATOR USING SUCH A FILTER

of which the following is a specification:

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FIELD OF INVENTION

This invention relates to a filter system with reduced switch thermal noise, and more particularly to such a system useful in ΣΔ modulators or converters and other sampling switched capacitor circuits.

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BACKGROUND OF INVENTION

Switched capacitor circuits used for processing signals such as in ΣΔ converters typically sample the input to such a converter and then sum it with the similarly sampled feedback signal. The difference in the summed signals is typically amplified, filtered, and/or quantized to provide the feedback signal and an output to subsequent systems. Inherent in switched capacitor circuits is the problem of thermal switch noise which is defined as:

$$Noise_{RMS} = \sqrt{\frac{kT}{C_{sample}}}$$

where T is the absolute temperature, C_{sample} is the value of the capacitor and k is a physical constant. Thus it can be seen that to reduce the noise by a factor of 2 the capacitance must be increased by a factor of 4. A substantial reduction in noise would require a large increase in the size of the capacitance: usually this is not desirable. One of the primary

limiting factors either in terms of the overall signal-to-noise ratio of the ΣΔ converter or in terms of the chip area is the size of the input sampling capacitor on the first integrator stage of the ΣΔ converter.

In ΣΔ converters oversampling is used in the quantizer and the oversampling rate (OSR) works to reduce the size of the capacitance to achieve a predetermined reduction in noise as expressed by the equation:

$$Noise_{RMS} = \sqrt{\frac{kT}{C_{sample} \cdot OSR}}$$

However, there is a limit to the OSR that can be applied, while the noise versus capacitance size problem persists. As can be seen from these expressions, the larger the input capacitor, the smaller the thermal noise stored on the capacitor due to the input switches. For very high-performance circuits with high signal-to-noise ratios, the size of the input sampling capacitor gets prohibitively large. Correspondingly, the complexity and power consumption of the driving amplifier increases as does the size of the sampling switches. The issue of "kT/C" noise (as the wide-band thermal noise is more popularly known) is valid in any sampled system using switches and capacitors and ΣΔ modulator A/D converters are only a subset.

SUMMARY OF INVENTION

It is therefore an object of this invention to provide an improved switched capacitor system with substantial reduction of switch thermal noise.

It is a further object of this invention to provide such an improved switched

capacitor system with substantial reduction of switch thermal noise which is useful in ΣΔ converters and other sampling switched capacitor circuits.

It is a further object of this invention to provide such an improved switch capacitor system with substantial reduction of switch thermal noise which reduces the input-referred thermal noise by a linear factor, or for the same noise the capacitor size may be reduced by an exponential factor.

One aspect of the invention is that for the same signal-to-noise ratio the size of the sampling capacitor can be reduced by the square of the gain of the difference amplifier.

The invention results from the realization that, in a feedback system where the output closely tracks the input, the error signal is small, and so rather than sample both the input and feedback signals before taking the difference to create the error signal, it is better to form the error signal with a continuous-time (non-sampling) circuit followed by a gain stage and then sample this amplified error signal using a switched-capacitor circuit. This arrangement causes the input-referenced switch thermal noise to be reduced by the amount of the gain used in the error path. The amount of gain that can be used in the error path depends on how closely the output tracks the input; it is desirable to make this gain as large as possible without causing the error signal to exceed the supply voltage.

This invention features a filter system with reduced switch thermal noise including an input circuit for receiving an input signal and a feedback signal and providing a signal representative of the difference. There is a filter circuit including at least an input sampling capacitor and switch which introduces thermal noise error and a feedback circuit responsive to the filter circuit for delivering to the input circuit the feedback signal. The input circuit includes means for amplifying the difference signal before it is submitted to the filter circuit

to reduce the input-referred thermal noise by a factor of approximately the gain of the amplification..

In a preferred embodiment the amplification may have a gain greater than one.

The invention also features a ΣΔ modulator with a filter system having reduced switch thermal noise including an input circuit for receiving an input signal and a quantized feedback signal and providing a signal representative of the difference. There is a filter circuit including at least an input sampling capacitor and switch which introduces thermal noise error and a quantizer circuit for quantizing the output of the filter circuit. A feedback circuit responsive to the quantizer circuit delivers to the input circuit the quantized feedback signal and the input circuit amplifies the difference signal before it is submitted to the filter circuit to reduce the input-referred thermal noise by a factor of approximately the gain of the amplification..

In a preferred embodiment the amplification may have a gain greater than one.

This invention also features a filter system with reduced switch thermal noise including a summing circuit for receiving an input signal and a feedback signal and providing a signal representative of the difference. There is a filter circuit including at least an input sampling capacitor and switch which introduces thermal noise error and a feedback circuit responsive to the filter circuit for delivering to the summing circuit the feedback signal. An amplifier circuit amplifies the difference signal before it is submitted to the filter circuit to reduce the input-referred thermal noise by a factor of approximately the gain of the amplifier circuit.

In a preferred embodiment the amplifier circuit may have a gain greater than one.

The invention also features a ΣΔ modulator with a filter system having reduced

switch thermal noise including an input circuit for receiving an input signal and a quantized feedback signal and providing a signal representative of the difference. There is a filter circuit including at least an input sampling capacitor and switch which introduces thermal noise error and a quantizer circuit for quantizing the output of the filter circuit. A feedback circuit responsive to the quantizer circuit delivers to the summing circuit the quantized feedback signal and an amplifier circuit amplifies the difference signal before it is submitted to the filter circuit to reduce the input-referred thermal noise by a factor of approximately the gain of the amplifier circuit.

In a preferred embodiment the amplifier circuit may have a gain greater than one.

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DISCLOSURE OF PREFERRED EMBODIMENT

Other objects, features and advantages will occur to those skilled in the art from the following description of a preferred embodiment and the accompanying drawings, in which:

Fig. 1 is a schematic diagram of a switched-capacitor system with reduced switch thermal noise according to this invention;

Fig. 2 is a schematic diagram of the switched capacitor system with reduced switch thermal noise according to this invention used in a ΣΔ modulator; and

Fig. 3 is a view similar to Figs. 1 and 2 with the input circuit implemented by a single component.

There is shown in Fig. 1 a switched-capacitor system 10 with reduced switch thermal noise including an input circuit 11 having a summing circuit 12 for receiving an input signal on input 14 and a feedback signal on feedback line 16 and providing an error signal on line 18 which is the difference of the two signals. There is a switched-capacitor

filter circuit 20 which includes a capacitor 22, charging switches 24 and 26, discharging switches 28 and 30, and integrating amplifier 32 which includes feedback capacitor 34. The combination of capacitor 22, switches 24-30, amplifier 32 and feedback capacitor 34 constitute a typical single-ended switched capacitor integrator circuit. While shown separately in Fig. 1 for illustrative purposes, switched capacitor circuit 20 is typically included as a part of the signal processor 36 labeled as H(z) which although typically a filter could be any signal processing function one form of which is a $\Sigma\Delta$ modulator. Switched capacitor circuit 20 and signal processor 36 may be thought of as the single switched-capacitor filter circuit 38.

In operation, switches 24 and 26 are closed to charge capacitor 22; then they are opened and switches 28 and 30 are closed to discharge capacitor 22 into amplifier 32. This recurring sampling causes an integration of the input signal by virtue of amplifier 32 and its feedback capacitor 34.

Input circuit 11 also includes an amplifier 40, having gain G, typically greater than 1, between error signal 18 and the sampling capacitor 22. In this way the error signal is amplified or gained up by the value of gain G. It can thus be seen that the thermal switch noise, when referred back to input 18, is reduced by a factor of the gain G thus substantially reducing the input-referred noise. Further, by summing (in summing circuit 12) the input signal 14 with the feedback signal from feedback circuit 16, which is close to the input signal on line 14, the difference produced as input 18 to amplifier 40, is quite small. Therefore, the gain G of amplifier 40 can be quite large and provide a substantial reduction in the input referred thermal switch noise without the voltage at the output of amplifier 40 exceeding the supply voltage.

The switched capacitor system 10 of Fig. 1 can be employed in a typical ΣΔ converter 50, Fig. 2, by adding a quantizer 52 at the output of signal processing circuit 36 so that feedback circuit 16 delivers to summing circuit 12 a quantized version of the output from signal processor 36 which is close to the input signal on line 14, resulting in a small difference signal on input 18 to amplifier 40 so that the gain can be maximized without the voltage at the output of amplifier 40 exceeding the supply voltage..

Although in Figs. 1 and 2 input circuit 11 is shown as two separate elements, summing circuit 12 and amplifier 40, this is not a necessary implementation of the invention as both functions can be accomplished in a single circuit such as summing amplifier 11a, Fig. 3.

Although specific features of this invention are shown in some drawings and not others, this is for convenience only as each feature may be combined with any or all of the other features in accordance with the invention.

Other embodiments will occur to those skilled in the art and are within the following claims:

What is claimed is:

1. A filter system with reduced switch thermal noise comprising:

an input circuit for receiving an input signal and a feedback signal and providing a signal representative of the difference;

a filter circuit including at least an input sampling capacitor and switch which introduces thermal noise error;

a feedback circuit, responsive to said filter circuit, for delivering to said input circuit said feedback signal; and

said input circuit including means for amplifying said difference signal, before it is submitted to said filter circuit to reduce the input-referred thermal noise by a factor of approximately the gain of the amplification.

2. The filter system with reduced switch thermal noise of claim 1 in which said gain is greater than one.

3. The filter system with reduced switch thermal noise of claim 1 in which said input circuit includes a summing circuit for receiving an input signal and a feedback signal and providing a signal representative of the difference and an amplifier circuit for amplifying said difference signal, before it is submitted to said filter circuit to reduce the input-referred thermal noise by a factor of approximately the gain.

4. A $\Sigma\Delta$ modulator with a filter system having reduced switch thermal noise comprising:

an input circuit for receiving an input signal and a quantized feedback signal and providing a signal representative of the difference;

a filter circuit including at least an input sampling capacitor and switch which introduces thermal noise error;

a quantizer circuit for quantizing the output of said filter circuit;

a feedback circuit, responsive to said quantizer circuit, for delivering to said input circuit said quantized feedback signal; and

said input circuit including means for amplifying said difference signal, before it is submitted to said filter circuit to reduce the input-referred thermal noise by a factor of approximately the gain of the amplification.

5. The ΣΔ modulator with a filter system having reduced switch thermal noise of claim 4 in which said gain is greater than one.

6. The ΣΔ modulator with a filter system having reduced switch thermal noise of claim 4 in which said input circuit includes a summing circuit for receiving an input signal and a feedback signal and providing a signal representative of the difference and an amplifier circuit for amplifying said difference signal, before it is submitted to said filter circuit to reduce the input-referred thermal noise by a factor of approximately the gain.

7. A filter system with reduced switch thermal noise comprising:

a summing circuit for receiving an input signal and a feedback signal and providing a signal representative of the difference;

a filter circuit including at least an input sampling capacitor and switch which introduces thermal noise error;

a feedback circuit, responsive to said filter circuit, for delivering to said summing circuit said feedback signal; and

an amplifier circuit for amplifying said difference signal, before it is submitted to said filter circuit to reduce the input-referred thermal noise by a factor of approximately the gain of said amplifier circuit.

8. The filter system with reduced switch thermal noise of claim 7 in which said amplifier circuit has a gain greater than one.

9 A ΣΔ modulator with a filter system having reduced switch thermal noise comprising:

a summing circuit for receiving an input signal and a quantized feedback signal and providing a signal representative of the difference;

a filter circuit including at least an input sampling capacitor and switch which introduces thermal noise error;

a quantizer circuit for quantizing the output of said filter circuit;

a feedback circuit, responsive to said quantizer circuit, for delivering to said summing circuit said quantized feedback signal; and

an amplifier circuit for amplifying said difference signal, before it is submitted to said filter circuit to reduce the input-referred thermal noise by a factor of approximately the gain of said amplifier circuit..

10. A ΣΔ modulator with a filter system having reduced switch thermal noise of claim 9 in which said amplifier circuit has a gain greater than one.

Applicant: Adams et al.
For: A Filter System With Reduced Switch Thermal Noise and a ΣΔ Modulator Using Such a Filter

ABSTRACT OF DISCLOSURE

A filter system with reduced switch thermal noise includes an input circuit for receiving an input signal and a feedback signal and providing a signal representative of the difference; a filter circuit including at least an input sampling capacitor and switch which introduce thermal noise error; a feedback circuit responsive to the filter circuit for delivering to the input circuit the feedback signal; the input circuit also amplifying the difference signal before it is submitted to the filter circuit to reduce the input-referred thermal noise by a factor of approximately the gain of the amplification; and a ΣΔ modulator using such a filter.

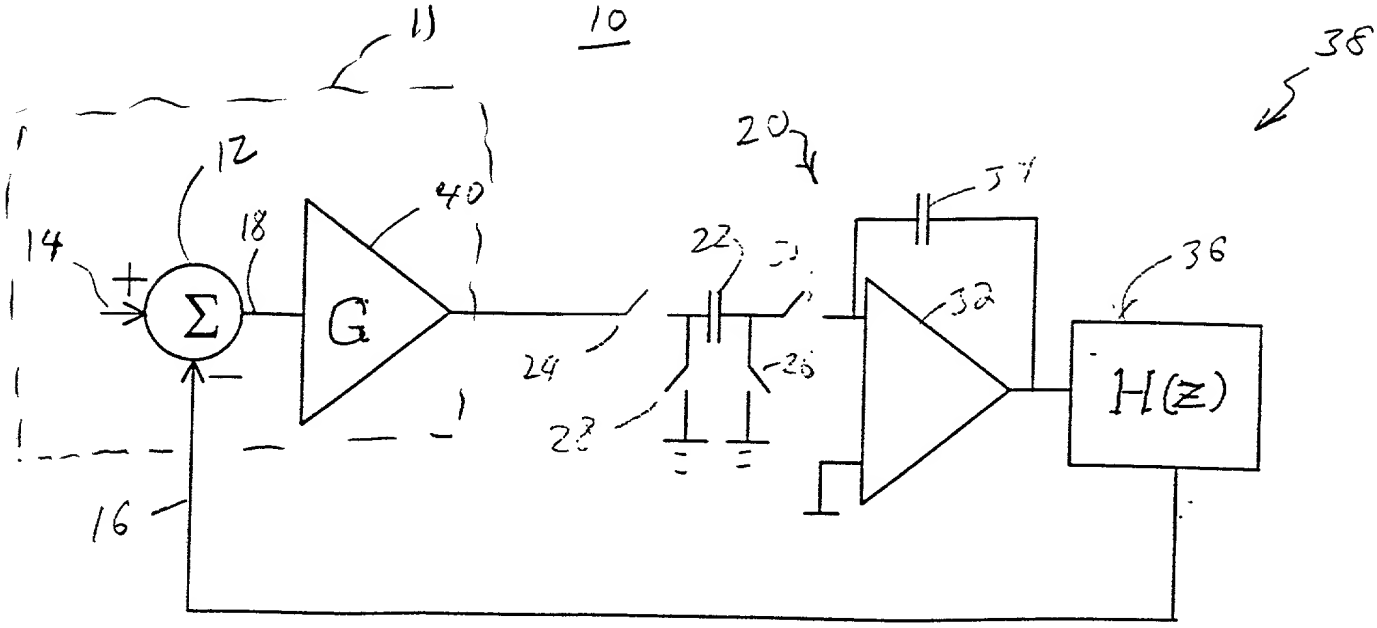
11
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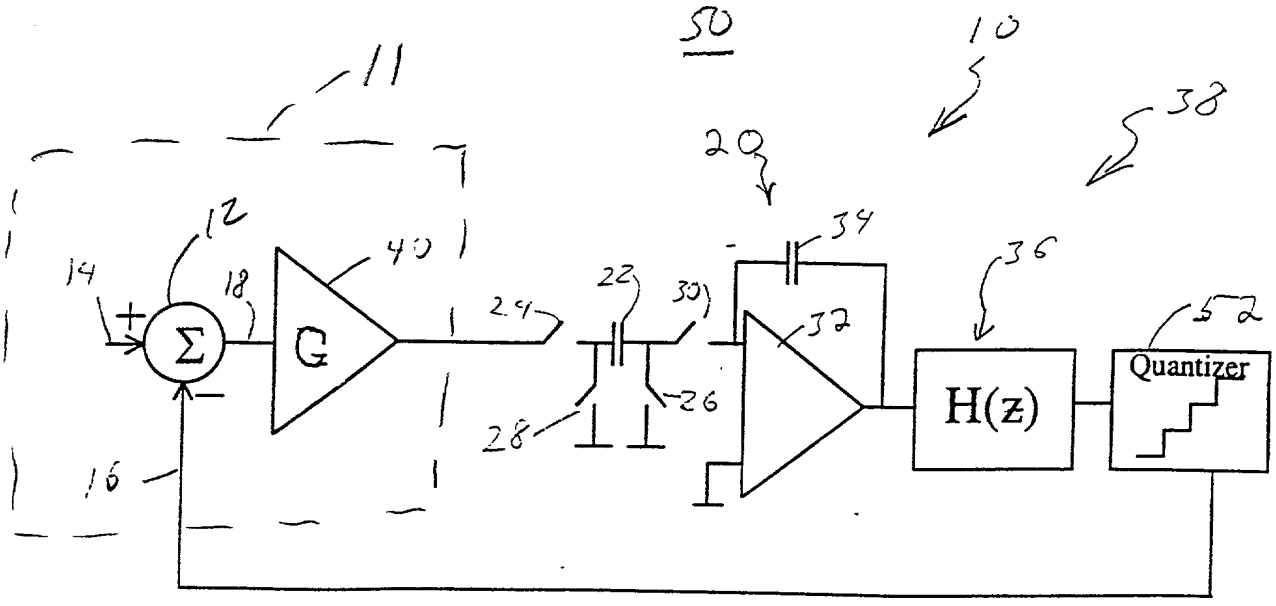
FIG. 1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Quantizer
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FIG. 2

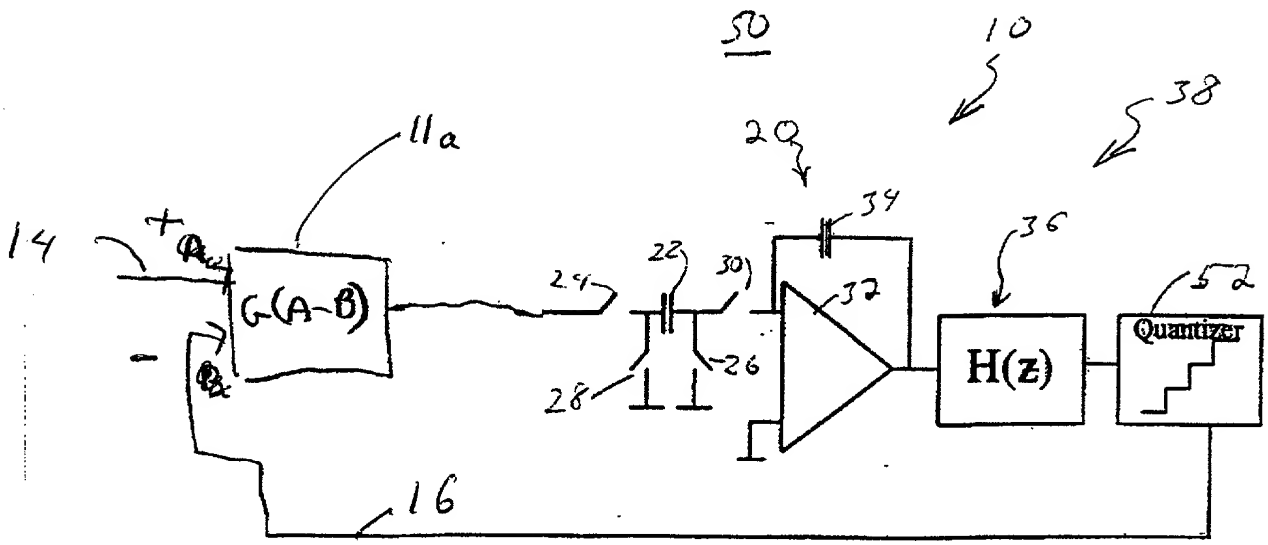

FIG. 3

COMBINED DECLARATION AND POWER OF ATTORNEY IN ORIGINAL APPLICATION	Attorney Docket No. AD-200J

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name; that

I verily believe that I am the original, first and sole inventor (if only one name is listed below) or a joint inventor (if plural inventors are named below) of the invention entitled: A FILTER SYSTEM WITH REDUCED SWITCH THERMAL NOISE AND A ΣΔ MODULATOR USING SUCH A FILTER described and claimed in the attached specification, that I understand the content of the attached specification, including the claims, that I do not know and do not believe the same was ever known or used in the United States of America before my or our invention thereof, or patented or described in any printed publication in any country before my or our invention thereof more than one year prior to this application, that the invention has not been patented or made the subject of an inventor's certificate issued before the date of this application in any country foreign to the United States of America on an application filed by me or my legal representatives or assigns more than twelve months prior to this application, that I acknowledge my duty to disclose information of which I am aware which is known to be material to patentability in accordance with 37 CFR 1.56, and that I have reviewed and understand the contents of the specification, including the claims, as amended by any amendment specifically referred to in the oath or declaration, and that no application for patent or inventor's certificate on this invention has been filed in any country foreign to the United States of America prior to this application by me or my legal representatives or assigns, except as follows: **None.**

I hereby appoint the following attorney(s) and/or agent(s) to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith:

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Reg. No. 23,095	Reg. No. 36,291	Reg. No. 42,522	Reg. No. 42,427

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I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

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Residence		Citizenship
Post office address		

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